Creare

REAL-TIME ROBOTIC CONTROL SYSTEM FOR TITANIUM GAS METAL ARC WELDING

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Creare Project 7404

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Disclaimer

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13. ABSTRACT (Maximum 200 words)

Titanium addresses the Army's need for high strength-to-weight characteristics and can meet the performance and transportability requirements of future lightweight systems. There are initiatives to develop low-cost titanium materials supplies; however, low-cost and high-rate fabrication processes are sorely lacking.

Welding and joining technologies enable improved manufactured components by reducing the weight, production time, and cost of joining parts. Improved welding technology increases product lifetimes and makes possible the fabrication of large structures. Gas Metal Arc Welding (GMAW) has the potential to significantly improve the quality, speed, and penetration depth of titanium welds, while reducing the cost per part. However, this result can only be achieved if proper weld parameters are selected and dynamically maintained during the welding process due to the nature of titanium.

During this Phase I SBIR project, we have successfully demonstrated the feasibility of our innovation by determining the requirements for the system for both Army and commercial applications; designing, fabricating, and testing one of the key sensors used in the adaptive control system; determining the hardware necessary to adequately measure the weld temperature for control use; and designing a prototype control system for Ti GMAWto be fabricated and tested during the Phase II project.

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1 INTRODUCTION

This is the final technical report for the Option Phase of a Phase I SBIR project that is being performed by Creare Inc. for the U.S. Army TACOM-ARDEC. It covers the time period between August 1, 2004 and December 1, 2004. The specific aim of this overall project is to develop a Real-Time Robotic Control System for Titanium (Ti) Gas Metal Arc Welding (GMAW) for current and future Army and commercial applications. GMAW is a particularly attractive welding process for Ti because of its potential for high deposition rate, deep penetration, and low cost. We are working to achieve our objective by developing an integrated system that will measure characteristics of the weld, the arc, and the metal transfer mechanism and use these data to adjust the weld current, voltage, and speed. Our system will make use of both existing weld hardware, new instrumentation, and computational algorithms to enable a significant improvement in the ability to weld Ti.

2 PROJECT SUMMARY

The Need. Joint Vision 2020 advocates for the development of flexible, effective, and efficient multi-dimensional forces capable of rapidly projecting overwhelming military combat power anywhere in the world. As part of this vision, the largest vehicles must be lighter than current mechanized systems with each system possessing common or multi-functional characteristics and capabilities. Thus, weight reduction is of primary importance to meet the operational objectives. Low-cost sources of titanium (Ti) are becoming available and, as a result, it is being employed in these and other systems to reduce weight significantly and enhance corrosion resistance. However, low-cost manufacturing technologies for Ti have not kept pace with the demand for high production rate and low cost. Most Ti alloys can be welded with typical arc welding processes. However, to consistently achieve high weld quality requires a proper gas mixture/shield, adjustment of the weld parameters, and, potentially, guidance for the weld arc that can wander substantially during the welding of titanium. Without substantial improvements to achieve a viable high-rate welding process, the benefits of titanium structures, components, and weapons will not be realized.

Creare's Innovation. The overall objective of this project is to develop a Real-Time Robotic Control System for Titanium Gas Metal Arc Welding (GMAW) (also known as Metal Inert Gas, or MIG Welding), for current and future Army and commercial applications. Pulsed GMAW, in particular, is an attractive welding process for Ti because of its potential for high deposition rate, deep penetration, and better control of droplet formation, transfer, and deposition resulting in low fabrication cost. Pulsed GMAW welding of titanium is not currently a standard practice, but has been shown to have great promise by the Army. For example, ARDEC has successfully fabricated titanium prototype receivers in support of the M240 Machine Gun Lightweight Initiative, the upper hull for a Composite Armored Vehicle (CAV) Integrated Hybrid Structure (IHS), and an all titanium mortar baseplate for the U.S. Marine Corps using robotic pulsed GMAW; however, before the process can be considered for production, real-time control of the process is mandatory.

We will achieve our objective by developing an integrated system that will continuously measure characteristics of the weld, the arc, and the metal transfer mechanism and use these data to adjust the weld current, voltage, speed, and arc concentration. Our system, shown schematically in Figure 1, will make use of both existing robotic weld hardware and new instrumentation and computational algorithms to enable a significant improvement in the ability to weld Ti. The Creare real-time weld control system will integrate: (1) feedback sensors such as weld width, weld temperature, droplet formation, detachment, and transfer; (2) adjustment of weld parameters such as current, arc length, and torch speed; and (3) real-time adaptive control algorithms that are used to make critical changes to the weld parameters during welding to achieve high-quality welds.

Phase I Results Prove Feasibility. During Phase I of this SBIR development project, Creare has clearly demonstrated the utility of our innovative Real-Time Robotic Control System for Titanium GMAW. During the Phase I base period, we: (1) determined the requirements for the system to be of use to both Army and commercial applications; (2) designed and fabricated a prototype of one of the sensors that will be used in the adaptive control system; (3) used the prototype sensor to measure the droplet formation and transfer during pulsed GMAW of steel and titanium; (4) determined the hardware necessary to adequately measure the weld temperature for control use; and (5) designed a prototype control system for Ti GMAW that can be fabricated and tested during the Phase II project. During the Phase I option period, we: (1) prepared to transition the conceptual design into a full-fledged design; (2) selected and ordered a weld pool temperature sensor; (3) performed the layout design of the overall system; (4) selected the welding power supply that would meet the needs of the Phase II system; and (5) determined the available high-speed cameras that would be appropriate for the droplet transfer measurement. During the Phase II effort, we expect to achieve all of the specifications to meet the Phase III applications by optimizing the hardware design, implementing the optimized hardware design, performing open loop tests to verify accuracy and dynamic range of the sensors, and demonstrating the use of our Real-Time Robotic Control System for Titanium GMAW using a pulsed power supply to control droplet formation on applications of interest at ARDEC.

The Benefits. The primary benefits of Creare's Real-Time Robotic Control System for Titanium Gas Metal Arc Welding include: (1) high quality titanium welds for use in critical fabrication and manufacturing processes; (2) high-speed welding that will reduce recurring manufacturing costs for lightweight structures; and (3) lower fixed costs because of the minimal capital equipment investment required for GMAW systems. This combination of benefits will enable the fabrication of very lightweight, very capable systems for use in future army systems. Commercial applications are equally numerous in the aerospace, automotive, and construction industries. Our system for pulsed GMAW welding of titanium is an enabling technology that could substantially expand the demand for titanium leading to the proliferation of titanium welded structures, which will correspond with the advent of lower cost titanium.

Commercial Potential. Our Real-Time Robotic Control System for Titanium Gas Metal Arc Welding has tremendous commercial potential. While the cost of titanium is dropping and new low-cost production processes are poised to drop the price further, there is no viable high-rate joining process that will enable the cost-effective fabrication of titanium structures. Our system will fill that void allowing titanium to reach its marketplace potential. As such, the proposed work is critical and has substantial commercial upside.

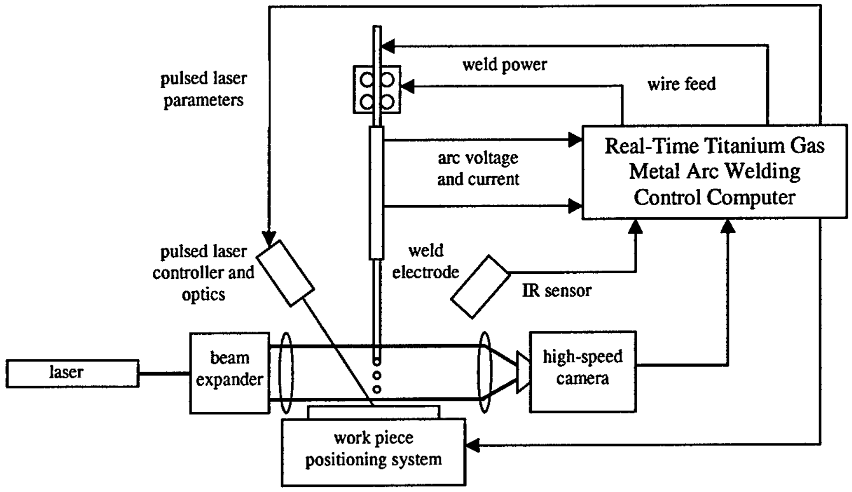


Figure 1. Conceptual Implementation of Creare's Real-Time Robotic Control System for Titanium Gas Metal Arc Welding. Our robotic GMAW control system uses advanced instrumentation sensors (laser backlight system for monitoring droplet characteristics and infrared temperature sensor for monitoring weld characteristics) to implement a real-time, adaptive control system. We will use these sensor measurements to determine optimized welding parameters. The development of an advanced pulsed laser to guide the arc size so arc placement is predictable and repeatable is to be funded under a separate non-SBIR effort along with its integration with the control system.

3 SIGNIFICANCE OF THE PROBLEM

Future Army Forces Need To Be Lightweight. A recent Defense Planning Guidance document states that the Army needs to develop an Objective Force that is capable of operational maneuvers from strategic distances; can penetrate and sustain operations in environments where access is denied; and be less dependent on traditional air and sea ports of entry and host nation support, reception, and infrastructure. The Army's responsibility to satisfy this requirement demands the development of a future full spectrum force that will be organized, manned, equipped, and trained to be strategically responsive, deployable, agile, versatile, lethal, survivable, and sustainable across the entire spectrum of military operations.

Titanium Is an Important Enabling Structural Material. Titanium and its alloys have proven to be technically superior and cost-effective materials for a wide variety of aerospace, industrial, marine, and commercial applications. Titanium addresses the Army's need for high strength-to-weight characteristics and can meet the performance and transportability requirements of lightweight systems. The use of titanium has the potential to achieve significant reductions in the mass of systems as compared to steel analogs. For example, the XM777 Lightweight Howitzer weight was reduced from 17,000 lbs to 9,000 lbs with a design that was based on using titanium structural components for approximately 80% of the vehicle. Furthermore, low-cost sources of bulk titanium are being developed to supply the material needed to employ Ti in future Army and commercial structures.

Welding Is a Critical Manufacturing Process. The need for higher quality, less expensive, and more robust products has helped to spur the development of welding processes. All manufactured products have joints that join different pieces of metal together. More often than not, the joints are the weakest part of the structure and the joint quality determines the quality of the end product. Welding and joining technologies enable improved manufactured components by reducing the weight, production time, and cost of fabricating quality joints. Improvements in welding have resulted in increased product lifetimes and enabled the fabrication of large structures.

Titanium Welding Is Particularly Difficult and Expensive. One of the factors limiting the use of titanium in military systems is the lack of an acceptable Gas Metal Arc Welding, GMAW (or MIG) welding process approved for military fabrications. Almost all titanium is welded using a laborious and time-consuming Gas Tungsten Arc Welding, GTAW (or TIG) process. In comparison, both steel and aluminum are capable of employing GMAW systems with significant productivity improvements of ten times the GTAW systems.

GMAW systems have not been employed successfully for titanium due to several constraints, which mostly contribute to interstitial contamination. Interstitial increases of O>500 ppm, N>50 ppm, and H>35 ppm are typical with GMAW systems currently available from equipment dealers. A large portion of this contamination is derived from the typical spatter generated during the process. This spatter or spitting of molten titanium to the outside of the protective gas coverage envelope leads to a potential re-ingestion of the contaminated material. Also, the turbulence of the protective gas stream from a turbulent arc leads to gas contamination. Some investigators have attempted to solve, with questionable success, these problems with extensive leading and trailing shields, which limit visibility and mobility of the weld torch, and thus limit the ability to weld structures of significance.

The factors controlling the spattering or spitting are well understood and have been largely addressed in the latest Gas Metal Arc Welding-Pulsed (pulsed GMAW) equipment produced from Lincoln Electric in their Power Wave 455 with computer wave control. This system, under the Army Titanium Manufacturing Technology Objective (MTO), has shown to have a dramatic reduction in spattering by incorporating a high-pulsed rate waveform, which also incorporates a pre-heat in each pulse. This micro-adjustment in wave shape or form is possible because the system is capable of being programmed (controlled) by a separate stand-alone computer.

Under the Titanium MTO, ARDEC is demonstrating the pulsed GMAW process on several applications of importance. One such example is the fabrication via pulsed GMAW process of an all titanium mortar baseplate for the U.S. Marine Corps (weight reduction from 135 lbs to 65 lbs). The baseplate demonstration illustrates the promise of pulsed GMAW. However, fabrication using pulsed GMAW still takes considerable operator intervention to adjust weld parameters due to the nature of titanium and arc interactions. Thus, before the process can be transitioned to the Army's production base, reliable real-time robotic control is needed to adjust the weld parameters dynamically during the fabrication process based on measured weld quantities.

4 PHASE I PROJECT RESULTS

The specific objective of the Phase I base project was to develop and demonstrate prototype instrumentation hardware for enhancing the quality and speed of performing titanium gas metal arc welding. During the Phase I Option project, we prepared to transition the conceptual design into a full-fledged design. During Phase II, we will combine the instrumentation, adaptive control algorithms, and real-time hardware in a complete control system for pulsed titanium GMAW.

In addition, during the Phase I project under separate funding, we developed and demonstrated the ability to control a plasma using a low-power pulsed laser. This innovation was developed for a separate purpose, but has wide ranging application to Ti pulsed GMAW. As a result of this additional innovation, the Army Titanium MTO plans to support integration of the plasma control process with the real-time control system that we will develop under the Phase II SBIR.

Creare's solution, shown schematically in Figure 1, is based on combining state-of-the-art sensor instrumentation, adaptive control algorithms, pulsed laser plasma concentration, and real-time hardware to measure and monitor the weld characteristics and modify the weld parameters in real time. Our Real-Time Robotic Control System for Titanium GMAW will consist of sensors for measuring characteristics of the weld, the arc, and the droplet formation and transfer and use these data to adjust the weld current, voltage, and speed. We expect that by combining these components into a complete robotic welding system that we will achieve higher quality, lower cost, and more robust titanium welds than are currently possible today. Below is a description of the work performed during the Phase I option period related to the overall hardware design, selection of a weld pool temperature sensor, and selection of the power supply hardware.

4.1 Overall Hardware Design

A schematic of the hardware design of our Ti GMAW system is shown in Figure 2. This figure shows that the hardware consists of the following:

1. Weld head. A commercial-off-the-shelf (COTS) system that contains the wire feed mechanism, shield gas handling plumbing, and the high power supply electronics. The wire feed and power supply can be controlled by the control computer.
2. Weld motion system. The motion system is used to move the work piece underneath the weld head. The motion system can be controlled by the control computer in order to set the proper weld speed.
3. Temperature sensor. The COTS temperature sensor is used to measure or estimate the weld temperature. Previous research has shown that this information can be used to estimate weld penetration which has been correlated with weld quality. This sensor signal will be input to the control computer and used to adjust the weld parameters.
4. Laser backlight system. The laser, optics, and high-speed camera are used to determine the metal transfer mechanism. This custom system can measure the drop formation and transfer and the data will be used to set the proper weld parameters.

During the Phase II project, we will generate the drawings required to fabricate our TI GMAW system, assemble the hardware, write the software required to interface the hardware to the control computer, and perform open- and closed-loop experiments to quantify the advantages of using our GMAW control system.

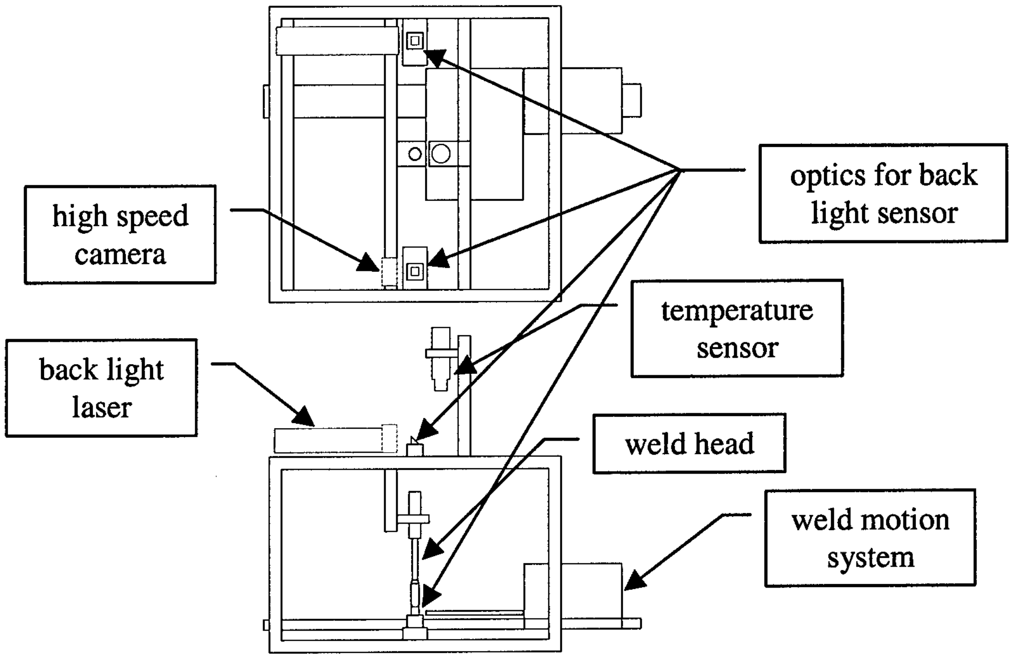


Figure 2. Drawing of Overall GMAW System Hardware. The overall design of the GMAW hardware is compact and flexible to allow reconfiguration and transport of the system.

4.2 WELD POOL TEMPERATURE SENSOR

The sensors make up some of the most important components of the robotic titanium weld control system. The sensors are used to observe and measure characteristics of the weld. These measurements then serve as the signal that is used to adjust the welding parameters. Several measurement techniques have been developed in order to measure the penetration depth (e.g., ultrasonic sensors, X rays, weld pool oscillations, optical devices, acoustic emissions, and infrared sensors) and the droplet formation and transfer. We will employ a laser backlight system for monitoring the droplet formation and transfer mechanism (described in the Phase I Base period final report) and infrared sensing to monitor aspects of the weld formation. Below is a description of each of the weld pool temperature sensors.

Infrared sensing has been used to monitor various aspects of the welding process for many years. Infrared cameras, thermocouples, and various combinations of these devices have been used to measure the temperature distribution around the weld pool in order to automatically track seams, control the bead width, or regulate the weld penetration. The temperature distribution near the weld pool provides important information on the status of the welding process. The weld parameters (voltage, current, and speed) and other process variables (joint mismatch, root gap, thickness of parts, and part composition) effect the pool shape (determined from temperature distribution), the absolute temperature near the pool, and the temperature distribution symmetry around the pool. Thus, by measuring the temperature distribution, many of the weld parameters and variables can be determined indirectly from the temperature.

All materials emit infrared radiation which is related to their temperature (i.e., thermal energy). The infrared spectrum encompasses electromagnetic wavelengths from 0.7 to 1000 microns and the intensity of radiation emitted by an object is a function of the temperature of the body and the surface emissivity (a material dependent property). If the emissivity of the material is known and the infrared radiation of the object is measured, the temperature can be determined using the Stefan-Boltzman formula.

The use of infrared sensors makes monitoring the temperature very convenient. Infrared sensors are inexpensive and the fact that they do not require contact between the sensor and the object (which is at high temperature), makes them easy to use for monitoring temperatures during welding. The sensors can be used on moving targets, in a vacuum, and in hostile or inaccessible regions. The sensors themselves have fast response and are easy to adapt to the floor of a shop or fabrication facility. The sensors convert the infrared radiant energy into electrical energy which can be used to monitor the temperature and extrapolate other important weld quantities. In our application, absolute accuracy is less important than repeatability since we will be using the sensor in a feedback control system. As long as the sensor measures the same reading when exposed to the same conditions, it is not as important that the sensor read the exact temperature.

During the Option period, we purchased the infrared temperature sensor shown below in Figure 3. We selected and purchased a Raytek smart infrared thermometer (model MA2SCSF). This sensor allows remote calibration, troubleshooting, and upgrade for sensors in difficult to reach locations (e.g., near the welding head). The ability of the sensor to perform in situ calibration to process temperatures is particularly helpful for the control of Ti GMAW. The sensor has a focal distance of greater than 27 in (67.5 cm) and a spot size of 0.04 in (1 mm) at the focal distance. This combination of optical characteristics will allow us to easily mount the temperature sensing hardware in a safe location and still allow sufficient flexibility in setting the location and size of the spot to be used for the temperature measurement.

In order to become familiar with the operation of the sensor, we connected the sensor to a computer and recorded data while the sensor was pointed at a standard desk lamp. These data are shown in Figure 4. The data were obtained with a sample rate of 10 Hz, which we anticipate being more than sufficient for controlling the weld parameters and is easily integrated into a computer-based weld control system. During the Phase II project, we will integrate the temperature sensor with the positioning system shown above and use the sensor in both open- and closed- loop tests of the Ti GMAW control system.

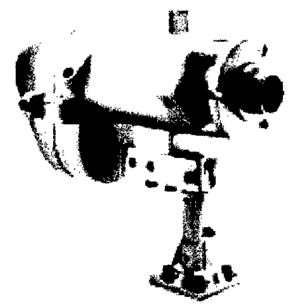


Figure 3. Picture of Infrared Temperature Sensor. This sensor can be used to monitor the temperature of the weld pool. The photo detector is connected to the control computer which processes the raw data to obtain the temperature.

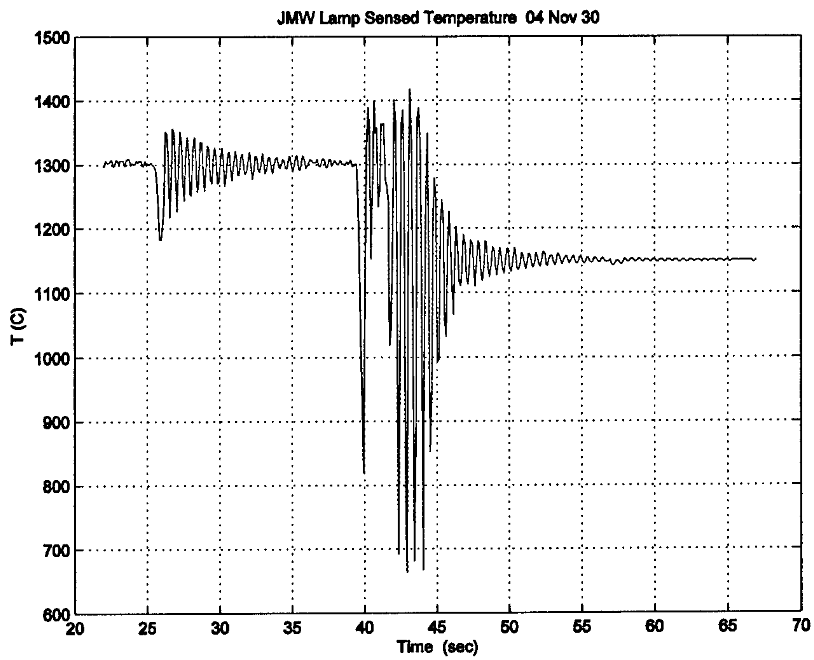


Figure 4. 10 Hz Measurement of Lamp Bulb Temperature; Temperature Variations Are Likely Due to Lamp Motion. (Temperature measurement is lower than color temperature of lamp light due to small area of filament.)

4.3 WELD POWER SUPPLY

The Creare Real-Time Robotic Control System for Titanium GMAW will be based on hybrid analog/digital control electronics. To achieve sufficient bandwidth, high precision control with algorithm flexibility, and power, a hybrid design is necessary. The analog electronics are used to implement the high bandwidth actuator power driver and the proper signal conditioning for the instrumentation sensors. A digital microprocessor will likely be used to implement the control algorithm for all of the controlled welding parameters. We expect to use a microcomputer because of the image processing that will be required to determine the droplet formation and detachment and the fact that a physics-based model will be required to infer important weld characteristics from the infrared sensor measurements. A block diagram of the real-time electronics hardware is shown in Figure 5. The weld drive electronics are described in greater detail below.

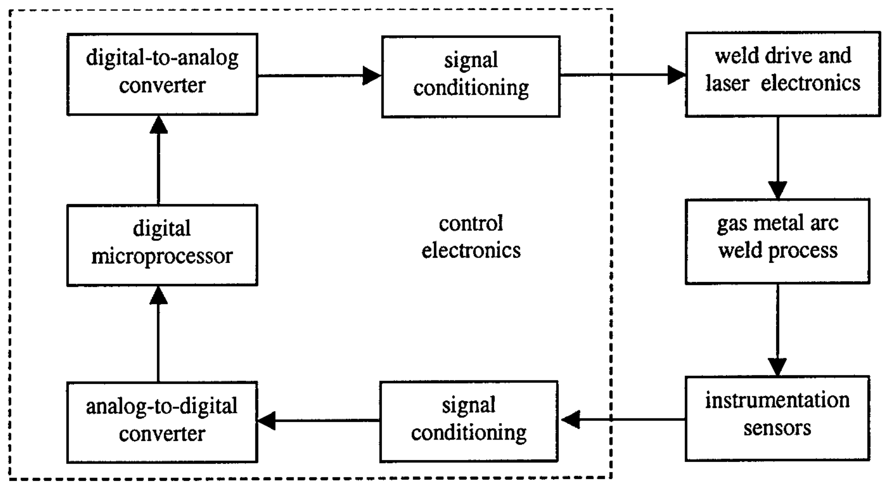
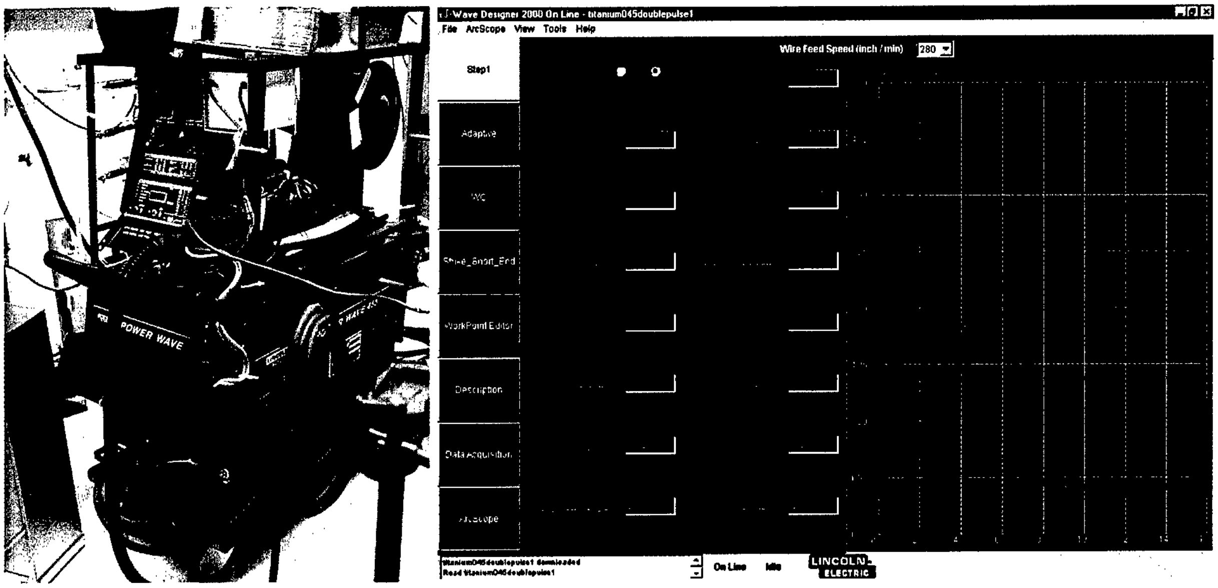


Figure 5. Block Diagram of Real-Time Electronics Hardware. This hardware is used to implement the adaptive control algorithm used to regulate the performance of the overall welding system.

In order to implement this control algorithm, we found that the Lincoln Electric Power Wave 455 with computer wave control (see Figure 6a) is an appropriate weld power supply. In the one drop per pulse mode, the droplet is formed when the current is pulsed and the background current is used to prevent the arc from extinguishing. In this mode, the melt rate of the wire is proportional to the pulse frequency, period, and level. The higher the frequency, the higher the average welding current and melting rate will be. Thus, the mass and heat transferred into the work piece can be controlled by regulating the background and pulsed welding current. As shown in Figure 6b, the pulse can be complicated for titanium GMAW. The first part of the pulse melts the end of the wire to form an attached droplet. Then the second multi-mode pulse first stretches the drop and then pinches it off to form the droplet that is transferred.

When the droplet has formed and is still attached, all of the weld current passes through the droplet. If the pulse current is held constant during this time, the droplet may overheat. If this happens, metallic vapor from the droplet will be generated and spatter may occur on the work piece. This results in the potential for significant loss of alloying elements in the weld. Thus, it is important to ensure that in this mode of operation the system will allow the average welding current and heat input to the work piece to be controlled while guaranteeing that the one drop per pulse mode of droplet transfer is sustained. Further, with the arc guidance and concentration provided by the pulsed laser, we expect to be able to guide the path of the droplet during transfer to the proper location in the weld (again, this laser guidance of the arc will be developed under separate funding). By combining these two effects, we can both control the drop transfer mode as well as the location of the drop in the weld.



(a) (b)

Figure 6. (a) Photo of Pulsed GMAW Power Supply. (b) Waveform Used to Affect Proper Transfer During the Pulsed GMAW.

5 CONCLUSIONS

Titanium addresses the Army's need for high strength-to-weight characteristics and can meet the performance and transportability requirements of current and future lightweight systems. There are initiatives to develop low-cost titanium materials supplies; however, low-cost and high-rate fabrication processes are sorely lacking.

Welding and joining technologies enable improved manufactured components by reducing the weight, production time, and cost of joining parts. Improved welding technology increases product lifetimes and makes possible the fabrication of large structures. Gas Metal Arc Welding (GMAW) has the potential to significantly improve the quality, speed, and penetration depth of titanium welds, while reducing the cost per part. However, this result can only be achieved if proper weld parameters are selected and dynamically maintained during the welding process due to the nature of titanium.

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